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Lead and thallium isotopes in the mass range 195-199

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With 13 figures in the text

Abstract

The following nuclides have been produced by irradiation of Tl in a synchro-cyclotron and studied in a β-spectrometer: 12.2 min Pb^{199m}, 1.5 hr Pb^{199}, 2.4 hr Pb^{198}, 42 min. Pb^{197m}, 37 min Pb^{196}, 17 min Pb^{195m}, 2.7 hr Tl^{197}, 2.4 hr Tl^{196} and 1.2 hr Tl^{195}. An electromagnetic isotope separator was used to make mass assignments.

All activities except Pb^{199m} seem to decay mainly by electron capture. In addition positron branches probably occur in several cases. Fragmentary decay schemes, supported in part by electron-electron coincidence measurements, have been constructed for the odd mass numbers.

A contribution to the knowledge of nuclear level systematics in this region with primary emphasis on the odd mass nuclei is also made.

1. Introduction

In 1954, when we started this investigation, very little was known about lead isotopes with mass number less than 200. 80 min Pb^{199} and 25 min Pb^{198} had been reported [1, 2], but mass assignments as well as half-life determinations were considered uncertain [3]. Nuclear spectroscopic data were entirely lacking.

The corresponding thallium isotopes, 7.4 hr Tl^{199}, 1.8 hr Tl^{198m} and 5.3 hr Tl^{198}, however, had shortly before been the subject of rather detailed studies [4, 5, 6]. We have not re-investigated the decay of these isotopes.

Some early results of our work concerning mass numbers 199, 198 and 197 have already been published [7]. Data and arguments from this preliminary report will, as a rule, be reproduced in the present communication without giving a reference.

Recently Knight and Baker [8] reported measurements on 2.8 hr Tl^{197} and 1.2 hr Tl^{195}, which, on the whole, agree with our results.

2. Experimental methods

2.1. *β- and γ-ray spectrometry*

A majority of the measurements were made in a β-spectrometer of the two-directional focusing type [9]. This instrument, having a mean radius of 18.5 cm, was normally adjusted to give a resolution of 0.3–0.4 % with a 1 mm source width and a solid angle of about 0.3 %.

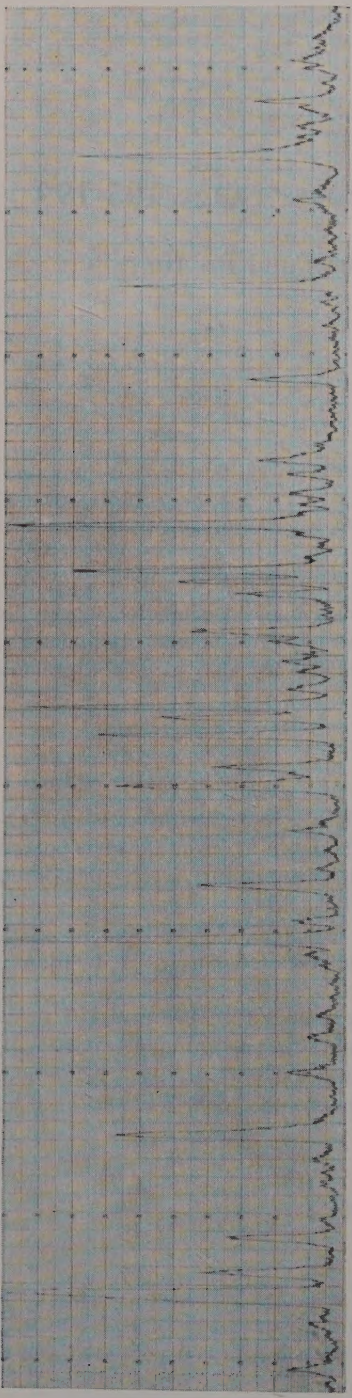

Fig. 1. Automatically recorded conversion electron spectrum of a type A sample (see section 2.3) from an 85 MeV irradiation. Energy range (from right to left): 50 keV–300 keV. Scanning time: 40 min. Sensitivity: full scale deflection = 100 counts/sec.

The investigation covers mainly the energy range 20–1000 keV of conversion electrons. In a preliminary study of the positron spectrum the spectrometer was run up to about 3 MeV.

The arrangement for automatic recording [9] was an especially useful feature in the present investigation because of the great complexity of the conversion electron spectra (cf. section 2.2) and the relatively short half-lives involved. Fig. 1 shows a typical record. Limited energy intervals were scanned repeatedly and the records analysed to give energies, intensities and half-lives of the different lines. The energy scale was initially established by means of several easily identified lines of heavier Pb and Tl isotopes, accurately measured elsewhere [10].

In order to improve energy and intensity determinations, many of the conversion lines were subsequently remeasured by point to point plotting. The accuracy of the energy values given in sections 3.2–3.6 of this report is estimated to be about 0.2 %.

The uncertainty in the decay rates calculated from the automatically taken records was found to be rather great, often several tens of per cent.[1] More careful half-life determinations have been carried out for all activities concerned by following the decay of suitable lines at fixed spectrometer conditions.

On the basis of the β-spectrometer measurements it was possible to construct some tentative decay schemes. Their validity was checked in a few important cases by electron-electron coincidence measurements in the double lense spectrometer of the Physics Department of this University [11]. Circular sources of 2 mm diameter were used, and the relative half-width in both channels was set at 1.5 %. The corresponding transmission was estimated to be about 2 %.

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[1] It is possible to achieve a considerably higher accuracy by choosing a long integration time and a correspondingly low scanning rate.

A few supplementary measurements were made in a single-channel scintillation spectrometer of conventional design, using a NaI(Tl) crystal as the detector. The poor resolving power of this instrument (about 10 % half-width at the 662 keV Cs^{137} peak) made it less well suited for use in this region of high γ-ray density.

2.2. *Production and mass assignment of activities*

Natural thallium (70.5 % Tl^{205} and 29.5 % Tl^{203}) was bombarded with protons of mean energies ranging from 45 MeV to 115 MeV in the synchro-cyclotron of this institute, yielding neutron deficient Pb isotopes by Tl $(p\,;xn)$ reactions. The Tl isotopes investigated were obtained as the daughters of corresponding Pb isotopes. It is true that radioactive Tl isotopes are also formed primarily in Tl $(p\,;p,xn)$ reactions, but then their separation from the bulk of inactive target material is not easily achieved.

To be able to choose a suitable bombarding energy for the production of a certain isotope one has to consider the excitation functions for various x-values. It is known that the probability of high x-values increases with increasing proton energy. For obvious reasons no experimental data were available pertaining to the reactions of interest. The near-lying case of Bi $(p\,;xn)$ reactions, however, had been studied by R. E. Bell [12]. His excitation curves for $x=3$, 5, 6 and 7 show some characteristic features. The peak cross sections decrease with increasing x. Further the curves are not symmetric but decrease more slowly on the high-energy side. This tendency becomes more pronounced with increasing x. Bell's measurements were found to agree reasonably well with theoretical predictions by J. D. Jackson [13], whose more extensive set of cross section curves we have used in order to derive the corresponding curves for Tl $(p\,;xn)$ reactions shown in Fig. 2.[1]

The general trend of the excitation functions as illustrated by this figure has two consequences which we want to point out.

(1) A high energy bombardment will produce a mixture of several Pb isotopes, which, together with their daughter activities, will cause a considerable line density in the conversion spectrum. That is, superpositions of lines are to be expected even in a high resolution spectrometer.

(2) A very careful experimental study of the yield curves would be needed in order to make valid mass assignments from excitation relations. In fact the situation is even worse than appears from Fig. 2, because of the energy spread of our proton beam. A half-width of about 15 MeV has been experimentally found [14], and this of course tends to smooth out the yield curves further. It should also be remarked that the unknown dependence of isomeric yield ratios on bombarding energy complicates the situation.

The natural way of overcoming these difficulties was to make use of our electromagnetic isotope separator [15] to prepare mass determined spectrometer sources (cf. [16]). Thus it proved possible to assign several conversion electron lines to mass numbers 199, 198 and 197. For intensity reasons, however, all measurements of line energies and conversion ratios had to be made with unseparated sources.

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[1] We are indebted to Dr. Bell and Dr. Jackson for communicating to us some of their results prior to publication.

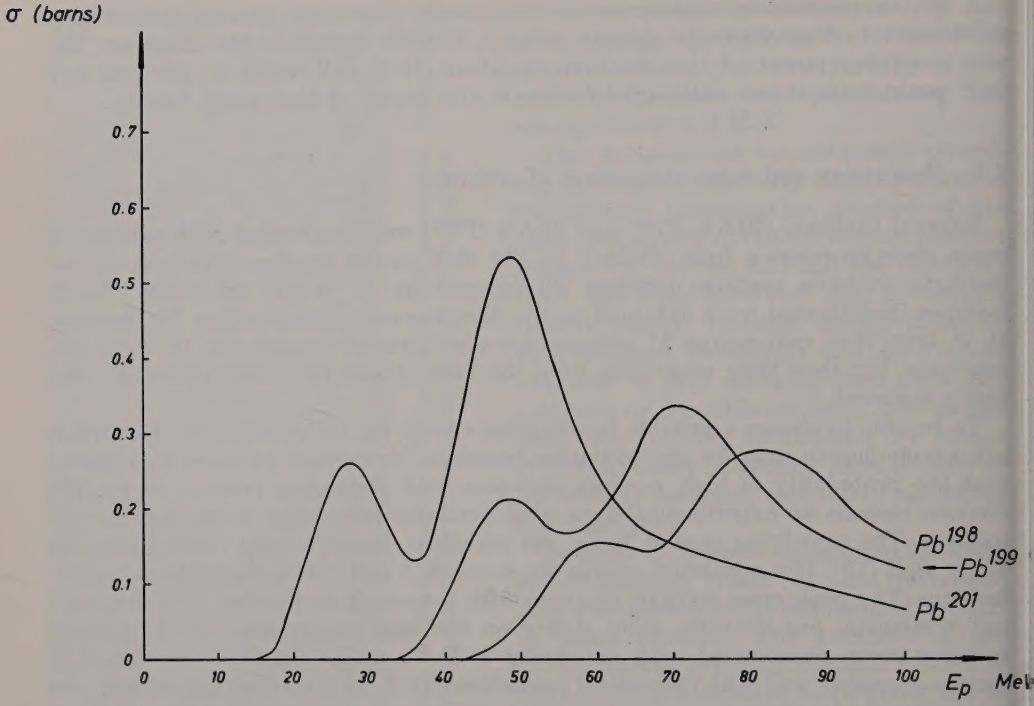

Fig. 2. Expected yields of some Pb isotopes from proton bombardment of natural Tl as a function of proton energy. Based on theoretical cross section curves worked out by J. D. Jackson [13].

Mass assignments of the half-lives, on the other hand, were confirmed by disintegration curves of mass separated samples for all mass numbers concerned.

2.3. *Preparation of β-spectrometer sources*

Five main types of source have been used, referred to in the following as A, B, C, D and E.

A. *Standard Pb samples.*—Radioactive Pb was chemically separated with a few μg carrier from the irradiated Tl targets (cf. [17]) and vacuum evaporated in the form of $PbCl_2$ onto thin Al backings (usually 1.8 mg/cm^2). This procedure takes about one hour, which is too long a time in relation to some of the half-lives dealt with. Another drawback is the relatively low efficiency (less than 50 %), caused mainly by losses in the vacuum evaporation. For these reasons the vacuum evaporation was sometimes skipped, and the Pb in hydrochloric acid solution directly evaporated on a suitable backing (Ag foil or organic film).

B. *Tl samples.*—Evidently type A sources will contain not only Pb isotopes but also their descendents formed by electron capture (and positron emission). In order to distinguish conversion lines following the decay of Pb isotopes from those due to elements of lower Z, Tl samples were prepared by ether extraction of Tl^{3+} from the

Pb fraction after a suitable decay period, reduction of Tl to the monovalent state, and vacuum evaporation of TlCl onto Al backings.

C. *Samples for rapid measurements.*—Narrow strips of Al foil, vacuum coated with a thin layer of natural Tl (about 1 mg/cm^2), were placed in the β-spectrometer immediately after a few minutes' irradiation. Such samples are too thick to allow precision measurements of electron energies and intensities, but they have proved very useful for special purposes, notably the determination of short half-lives.

D. *Mass separated samples.*—After chemical treatment similar to type A samples but with more carrier (about 2 mg Pb) added, Pb was fed to the ion source of the mass separator as $PbCl_2$. The ion beams of the mass numbers to be studied were collected on narrow strips of Al foil. In order to establish the mass scale, the beams corresponding to stable Pb isotopes were observed on a fluorescent screen throughout the runs. The half-width of the lines was kept at about 1.5 mm in the focal plane, where the distance between neighbouring masses around $A = 200$ is equal to 3.5 mm.

E. *Samples by electrodeposition.*—In the search for a rapid and efficient method of sample preparation we have made some promising experiments with electrodeposition. Though the procedure is not yet sufficiently tested, a brief description may be of interest. After the Tl had been removed by chemical separation, the Pb solution was slightly acidified with nitric acid and transferred to an electrolysis vessel with a 1 mm strip of Pt foil as the anode (cf. [18]). About 20 minutes' electrolysis at increased temperature (80°C) was sufficient to bring the main part of the Pb in the form of PbO_2 to the anode, which was then used as a β-spectrometer source. The time required for the whole procedure was 45 minutes and can no doubt be further reduced. Pt, however, is far from an ideal backing material; this seems to be the main disadvantage of the method in its present form.

3. Results

3.1. *Treatment of experimental data*

In sections 3.2–3.6 the mass numbers will be discussed in descending order. Only those transitions have been included, whose mass assignment is reasonably well established by mass separation, genetic relationship or satisfactory half-life determination. A number of unassigned lines have been collected in a separate table in section 3.7.

The relative K-electron intensities (I_{e^-}) given in the tables are normalized to the strongest line of each activity. Corresponding total transition intensities (I_{tot}) are directly calculated from the K-electron intensities, in some cases after very rough estimates of multipole mixing ratios.

In order to make multipole assignments of γ-transitions we have compared the measured K/L and $L_{\text{I+II}}/L_{\text{III}}$ ratios with those calculated from the conversion coefficient tables of M. E. Rose *et al.* [19]. These tables do not take into account the rather pronounced influence of the finite size of the nucleus in the mass region concerned [20, 21]. This tends to reduce the K and L_{I} coefficients but should not affect L_{III} appreciably. As to L_{II} the situation is unclear. Thus a non-negligible error may be introduced into the theoretical conversion ratios. The effect becomes serious when measured K-electron intensities are used in calculating total relative transition probabilities. The K conversion coefficients entering these calculations have been

Table 1. Transitions in A = 199.

Nuclide	E_γ keV	E_{e-} keV	Conversion		I_{e-}	$K/\Sigma L$	L_{I+II}/L_{III}	Multipole order	I_{tot}	Remarks
			Shell	Element						
Pb^{199m}	424.1	336.1	K	Pb		1.9	3.2	$M4$		$M4$ calc.: $K/\Sigma L =$
12.2 ± 0.3 min		408.6	L_{I+II}							$L_{I+II}/L_{III} =$
		411.1	L_{III}							
		420.1	M							
		423.1	N							
Pb^{199}	352.8	267.3*	K	Tl	39	5.3	40	$M1+E2$	420	$M1$ calc.: $K/\Sigma L = 6$
1.5 ± 0.2 hr		337.8	L_{I+II}						(75 % $M1$)	$L_{I+II}/L_{III} = 1$
		340.4	L_{III}							$E2$ calc.: $K/\Sigma L = 2$
										$L_{I+II}/L_{III} = 4$
										Indicates ≈ 75 % M
	367.0	281.5*	K	Tl	100	4.4	7.4	$M1+E2$	2010	$M1$ calc.: $K/\Sigma L = 6$
		351.9	L_{I+II}						(30 % $M1$)	$L_{I+II}/L_{III} = 1$
		354.2	L_{III}							$E2$ calc.: $K/\Sigma L = 2$
		363.0	M_I							$L_{I+II}/L_{III} = 4$
										Indicates ≈ 30 % M
	721.0	635.5	K	Tl	2					L-line superimposed

* Present in mass 199 β-spectrum.

taken from recent tables prepared by L. Sliv [21] for non-point distribution of the nuclear charge. (Sliv's data on L shell conversion have not yet appeared.)

In the choice between different M-subshells we have applied the results of E. L. Church and J. E. Monahan [22].

For conventional reasons single particle notation has been used in the discussion of all nuclear energy levels concerned. It should be remarked, however, that in many cases this may not represent the true nature of the level.

In the decay schemes experimentally established coincidences are indicated by large dots in accordance with the convention used in Nuclear Science Abstracts.

3.2. *A = 199*

In addition to the well-known 7.4 hr Tl^{199} [4], the disintegration curve of a mass 199 sample showed two other components of 1.5 hr and about 10 min half-life. Conversion lines of two γ-transitions (353 keV and 367 keV) of the longer period were present in the mass 199 β-spectrum. They were not found with a type B sample and thus must belong to the decay of a Pb isotope. As the conversion of both transitions definitely occurs in Tl, we conclude that the 1.5 hr activity is due to the ground state of Pb^{199}. This is in agreement with the previously reported 80 min period for this isotope [1].

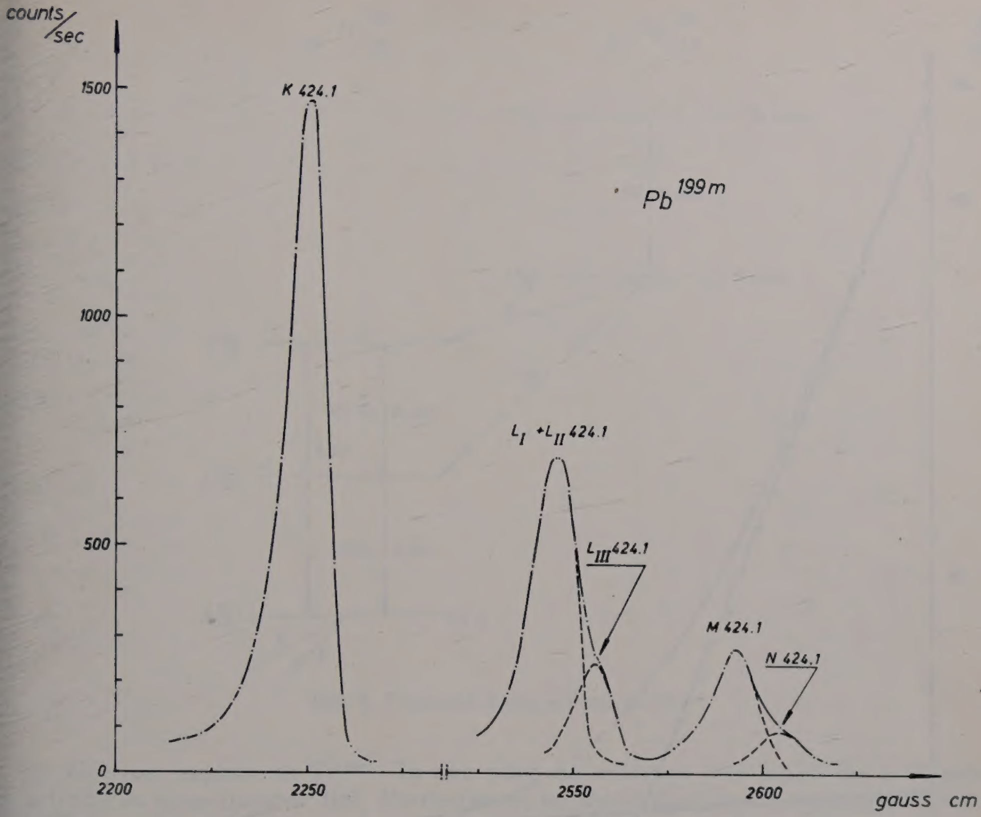

Fig. 3. Conversion lines of the 424 keV isomeric transition in Pb^{199m}.

The detection of conversion lines corresponding to the 10 min activity in the β-spectrum of mass 199 was prevented by the short half-life. With type A samples, however, K, L, M and N lines of a 424 keV transition of 12 min half-life were found. Energy measurements showed conversion in Pb, and intensity ratios pointed unambiguously to an $M4$ transition (Fig. 3). These facts lead to the assignment Pb^{199m}.

The half-life was determined as 12.2 ± 0.3 min by following the decay of the K-line in the β-spectrometer, using a type C sample (Fig. 4).

The nuclear spectroscopic data are listed in Table 1. Tl^{199} is not included because our work did not add any new information about this isotope.

According to nuclear shell theory the $M4$ transitions in odd neutron nuclei near the end of the 126 shell should take place between the levels $i_{13/2}$ and $f_{5/2}$. At the time when Pb^{199m} was discovered, the ground state of Pb^{199} was expected to be $p_{3/2}$ rather than $f_{5/2}$. This implied another γ-ray in cascade with the isomeric transition. In spite of considerable efforts, however, no second γ-transition was found, neither with the β-spectrometer, nor with the scintillation spectrometer. This negative result was confirmed by Stockendal *et al.* [23], who produced Pb^{199m} by milking from Bi^{199}. Thus it seems fairly certain that the Pb^{199} ground state is $f_{5/2}$, though a second γ-ray of very low energy (< 30 keV) cannot be excluded.

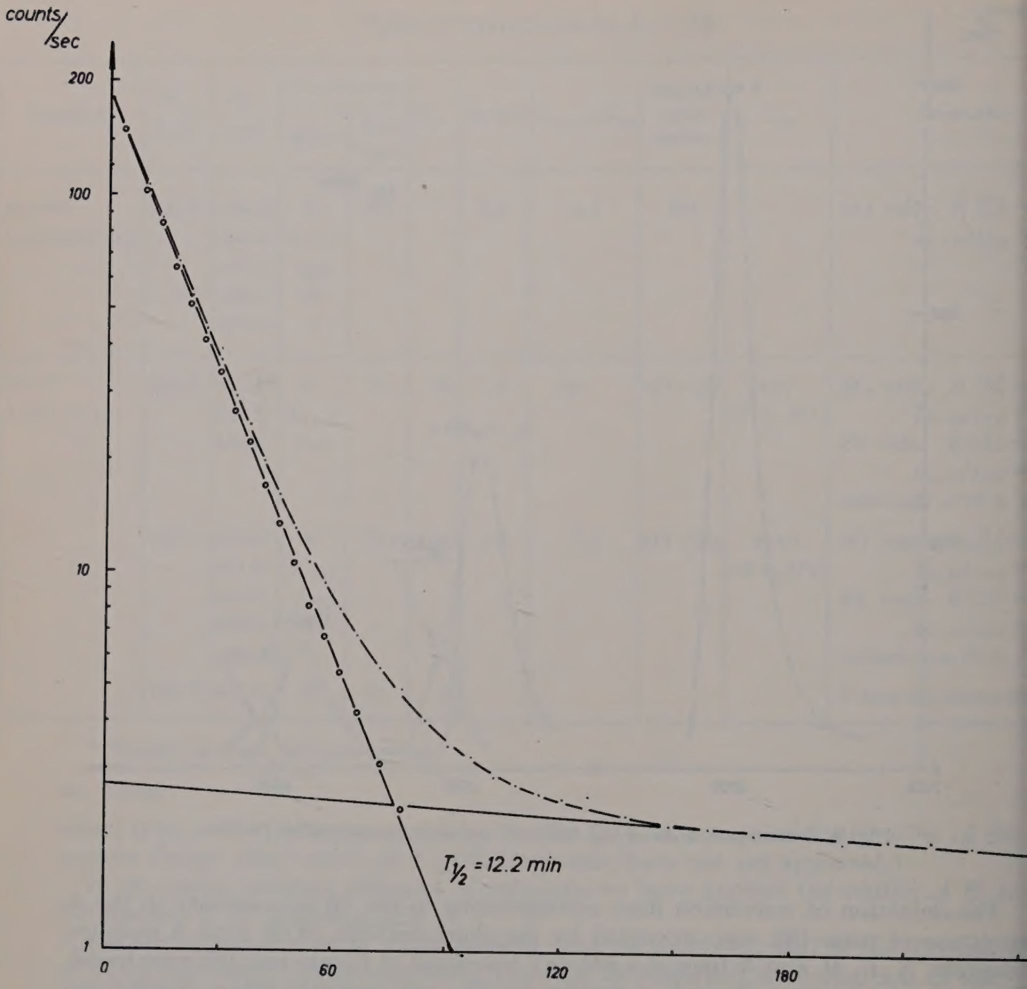

Fig. 4. Decay of the *K* line of the 424 keV isomeric transition in Pb^{199m}.

Measurements of $e^{-}-e^{-}$ coincidences have proved the cascade relation between the 353 keV and 367 keV γ-rays, also indicated by the weak 721 keV cross-over transition. As further discussed in section 4.2 multipolarities and intensities lead to the assumption that the 367 keV transition connects the first excited state of Tl^{199} ($d_{3/2}$ in single particle notation) with the ground state ($s_{1/2}$), while the 353 keV transition goes between the second and the first excited states ($d_{5/2}$ and $d_{3/2}$ respectively).

A decay scheme, consistent with these data, is shown in Fig. 5.

3.3. *A = 198*

From their study of 1.8 hr Tl^{198m}, Passell *et al.* [6] concluded that the 25 min half-life assigned to Pb^{198} [2] was due to a high spin isomeric state, decaying directly

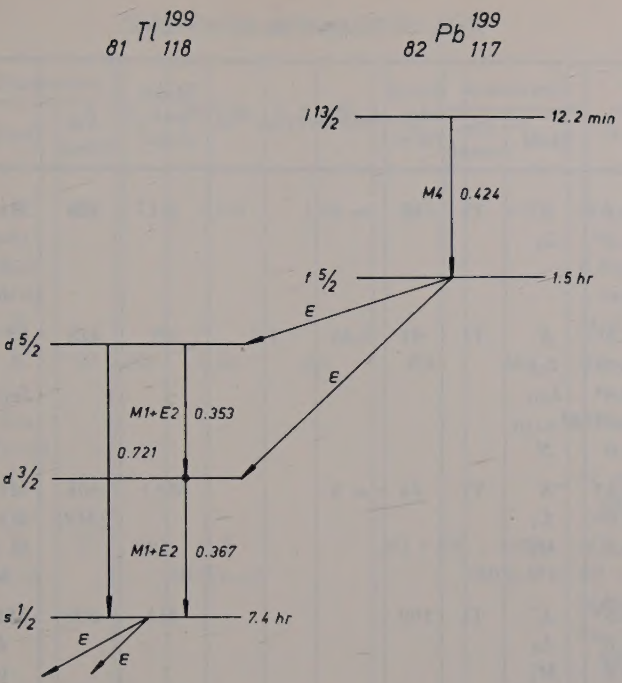

Fig. 5. Proposed decay scheme of Pb^{199}.

by electron capture to Tl^{198m}. In our work no evidence was found for a 25 min activity at mass number 198. Furthermore, no conversion lines belonging to 1.8 hr Tl^{198m} were seen. We have indeed a 2 hr γ-ray of very nearly the same energy as the 261 keV $M4$ transition found by Passell *et al.* [6]. Though fairly strong in a type A sample it did not, however, show up in the Tl fraction, and the multipole order is certainly lower than $M4$. Thus we have assigned it to the Pb^{198} ground state, which was shown to have the half-life 2.4 hr by similar reasoning as was used in the case of the Pb^{199} ground state.

The most plausible explanation of the absence of Tl^{198m} seems to be that the corresponding high spin state in Pb^{198} is not identical with the 25 min activity as suggested by Passell *et al.* [6], but is so short-lived that it decays considerably before the chemical separation of Pb from the Tl target. According to Bergström and Wapstra [24] a rather fast $E4$ $(9^- \rightarrow 5^-)$ transition may determine the half-life in this case instead of the $E5$ $(9^- \rightarrow 4^+)$ transition responsible for the isomeric states of Pb^{204} and Pb^{202}.

Table 2 summarizes the results of our β-spectrometer measurements on Pb^{198}.

For intensity reasons the 173 keV $E2$ transition probably goes to the ground state. Preliminary coincidence measurements between some of the other γ-rays gave the following result:

365.5 keV–290.4 keV	Yes
365.5 keV–382.0 keV	No
365.5 keV–397.8 keV	Yes
397.8 keV–290.4 keV	No

Table 2. Transitions in A = 198.

Nuclide	E_γ keV	E_{e^-} keV	Conversion		I_{e^-}	$K/\Sigma L$	L_{I+II}/L_{III}	Multipole order	I_{tot}	Remarks
			Shell	Element						
Pb^{198} 2.4 ± 0.2 hr	116.9	31.4 101.6*	K L_I	Tl	85	≈ 4		$M1$	128	$M1$ calc.: $K/\Sigma L = 6.0$; sence of L_{III} and nar L-line supports ass ment $M1$.
	173.4	87.9* 158.6* 160.8* 170.2* 172.0	K L_{II} L_{III} M_{II+III} N	Tl	61	0.65	1.2	$E2$	448	$E2$ calc.: $K/\Sigma L = 0.74$; $L_{II}/L_{III} = 1.6$. $L_{II}/M \approx 2$; $M/N \approx 2$.
	259.3	173.8* 244.0* 255.8	K L_I M_I	Tl	54	≈ 3		$M2$?	108 ($M2$)	$M2$ calc.: $K/\Sigma L = 4.2$; $M1$ calc.: $K/\Sigma L = 6.7$. L_I composite with Pb^{2} line. $K/M \approx 5$.
	290.4	204.9* 275.5 286.9	K L_I M_I	Tl	100			$M1$	400	$M1$ based on absence L_{III}; L-lines superim posed.
	365.5	280.0* 350.0* 363.0	K L_I M_I	Tl	100?	> 2 ?				All lines composite w Pb^{199} lines.
	382.0	296.5 378.4	K M	Tl	19					$K/M \approx 17$; L masked Pb^{201} line. Assignment not quite c tain.
	397.8	312.3 382.6 384.8	K L_{I+II} L_{III}	Tl	10	2	2	$E2$?	308 ($E2$)	$E2$ calc.: $K/\Sigma L = 2.6$; $L_{I+II}/L_{III} = 5.4$. Assignment confirmed coincidence with 365.5 keV transition

* Present in mass 198 β-spectrum.

The information gathered so far is not sufficient to allow the construction of a decay scheme.

3.4. *A = 197*

Conversion lines of two different half-lives, 42 min and 2.7 hr, were seen in the β-spectrum of a mass 197 sample. From measurements on a type B sample it was concluded that they are due to a Pb and a Tl activity respectively. One of the 42 min transitions (234 keV) was found to convert in Pb. The relative intensities of its con-

Table 3. Transitions in A = 197.

ide	E_γ keV	E_{e-} keV	Conversion		I_{e-}	$K/\Sigma L$	L_{I+II}/L_{III}	Multi-pole order	I_{tot}	Remarks
			Shell	Ele-ment						
7m 2 n	234.0	146.0* 218.4* 221.2* 230.4 233.0	K L_I L_{III} M_{III} N	Pb	77	> 0.3	1.5	$M4$	212	$M4$ calc.: $K/\Sigma L = 0.83$; $L_{I+II}/L_{III} = 1.4$. L-lines composite with M and N 221.9 keV. $M/N = 3.5$.
	221.9	136.4* 207.1* 209.1* 218.9* 221.0*	K L_{II} L_{III} M_{II+III} N	Tl	100	0.28	2.5	$E3$	889	$E3$ calc.: $K/\Sigma L = 0.27$; $L_{I+II}/L_{III} = 3.8$. $E2$ calc.: $K/\Sigma L = 0.80$; $L_{I+II}/L_{III} = 2.3$. M and N composite with 234.0 keV L-lines.
	384.8	299.3* 369.4	K L_{I+II}	Tl	88	5.7 (K/L_{I+II})		$M1+E2$	1430 (60% $M1$)	$M1$ calc.: $K/L_{I+II} = 6.6$; $E2$ calc.: $K/L_{I+II} = 3.0$. Indicates ≈ 60 % $M1$. L_{III} composite with L_I 386.7 keV.
	386.7	301.2* 371.4	K L_{I+II}	Tl	56	3.5		$M1+E2$	1510 (10% $M1$)	$M1$ calc.: $K/L_{I+II} = 6.6$; $E2$ calc.: $K/L_{I+II} = 3.0$. Indicates 10 % $M1$. L_I composite with L_{III} 384.8 keV.
 0.2	133.5	50.4 119.5* 121.7* 131.2 132.7	K L_{II} L_{III} M_{II+III} N	Hg	6	0.4	1.4 (L_{II}/L_{III})	$E2$	55	$E2$ calc.: $K/\Sigma L = 0.40$; $L_{II}/L_{III} = 1.4$. $L_{II}/M = 2.6$; $M/N = 2$.
	151.7	68.6* 137.2* 148.5 151.4	K L_I M_I N	Hg	100	5.2		$M1$	170	$M1$ calc.: $K/\Sigma L = 6.1$. Absence of L_{III} supports $M1$. L_I composite with K 221.9 Pb^{197m}.
	173.1	90.0* 160.2	K L_I ?	Hg	2	5		$M1$?		$L/M = 3$; $M/N = 2$.

* Present in mass 197 β-spectrum.

version lines indicate the multipolarity $M4$ (Fig. 6). Therefore the 42 min activity was assigned Pb^{197m}.

A type C sample was used in determining the half-life as 42 ± 2 min (Fig. 7).

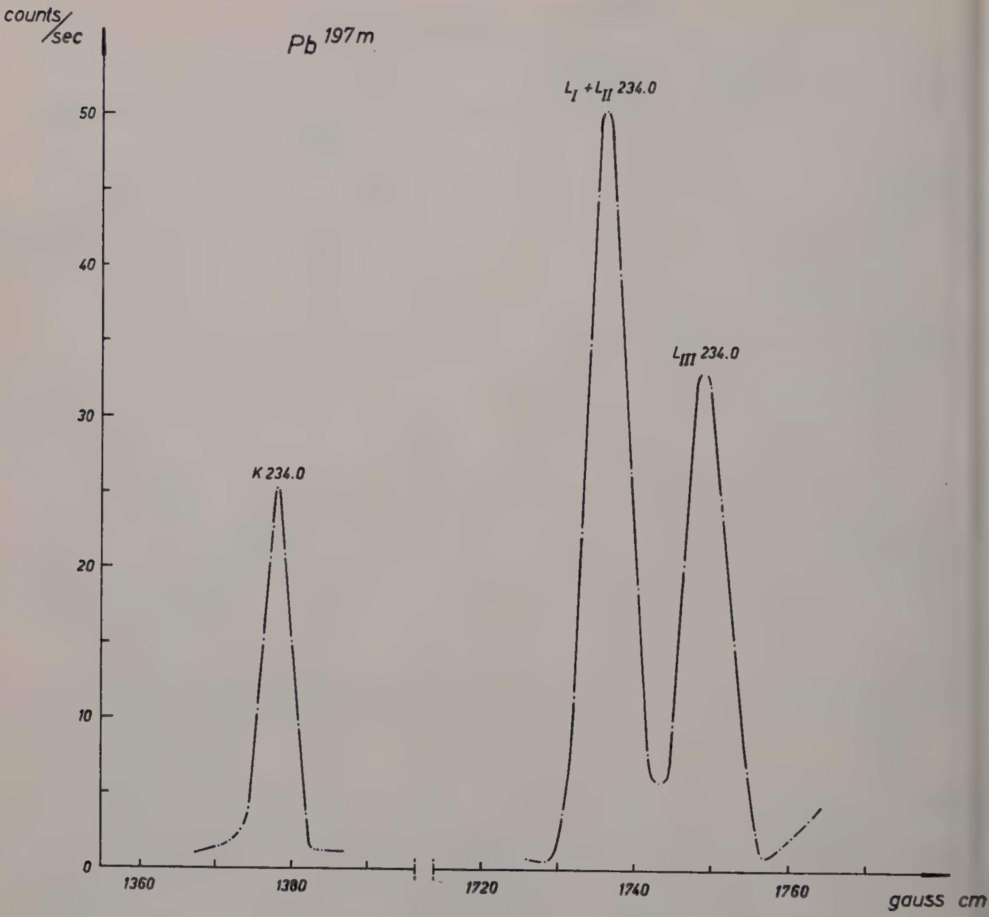

Fig. 6. Conversion lines of the 234 keV isomeric transition in Pb^{197m}.

Nothing is known with certainty about the lifetime of the Pb^{197} ground state. All lines ascribable to Pb^{197} decay with the 42 min period. Thus it may be guessed that the half-life of the ground state is small compared with that of the isomer.

The 2.7 hr lines are all converted in Hg and for that reason assigned to Tl^{197}. This assignment was recently confirmed by Knight and Baker [8], who produced Tl activities from enriched Hg targets by deuteron bombardment and from Au by alpha particle bombardment.

Table 3 lists our conversion electron data.

In analogy with the situation in Pb^{199m} no second γ-ray was found in cascade with the 234 keV isomeric transition. Thus also the Pb^{197} ground state seems to be $f_{5/2}$.

A cascade relation 222 keV–385 keV–387 keV was established by means of $e^- - e^-$ coincidences. The last two transitions are identified as $d_{5/2} \rightarrow d_{3/2}$ and $d_{3/2} \rightarrow s_{1/2}$ (cf. Pb^{199}), but their order is somewhat uncertain. The K/L ratio of the 222 keV γ-ray fits the multipole assignment $E3$ very convincingly, indicating a $h_{11/2} \rightarrow d_{5/2}$ transition.

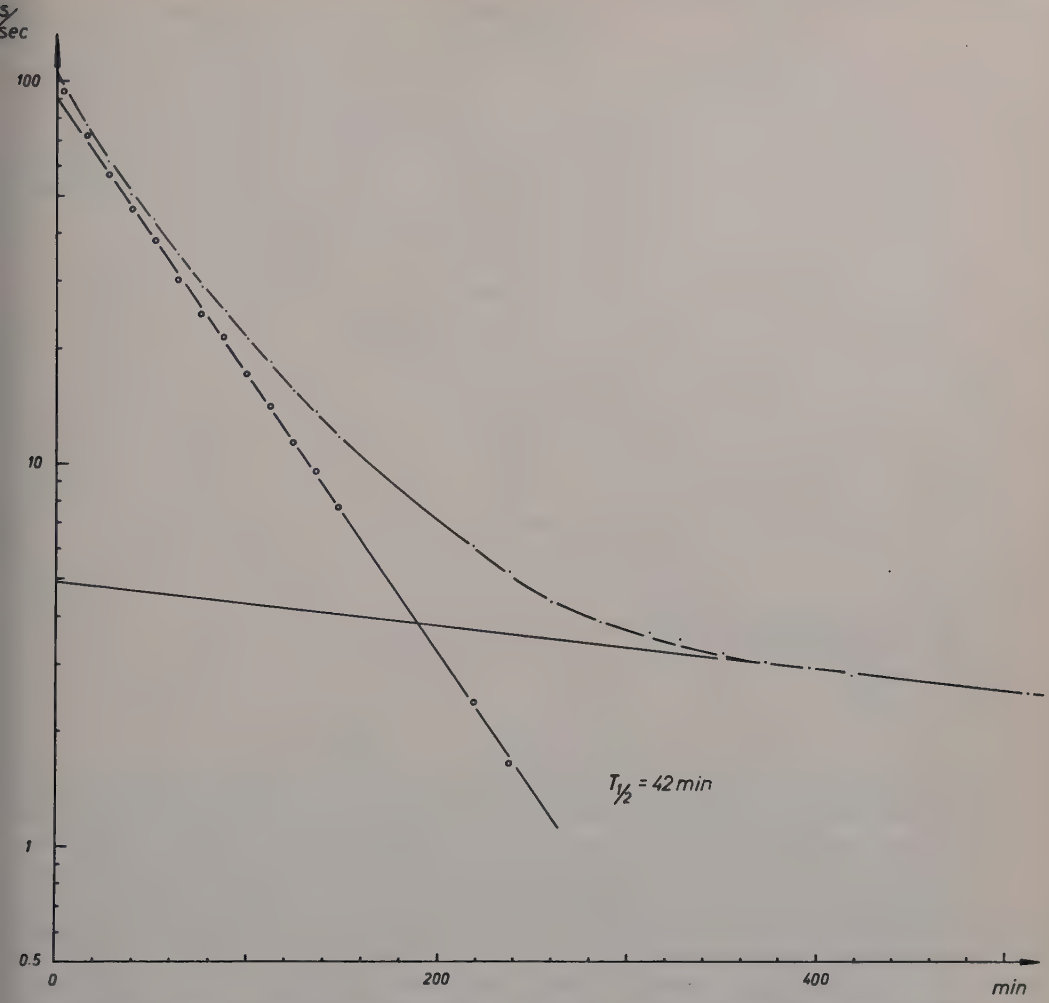

Fig. 7. Decay of the K line of the 387 keV transition following the electron capture of Pb^{197m}.

As the 11/2 state can hardly be reached from the Pb^{197} ground state ($f_{5/2}$) because of the spin difference, an E.C. branch from Pb^{197m} must be postulated. From the intensities of the 222 keV and the 234 keV transitions the branching ratio E.C./I.T. = 4.2 ± 0.3 is obtained. This will be further discussed in section 4.1.

We have not yet been able to measure the lifetime of the $h_{11/2}$ level. A 0.54 sec half-life, however, associated with a 384 keV γ-ray, was reported by Henrikson *et al.* [25] and ascribed to Tl^{197m}. Most probably this transition, studied in a scintillation spectrometer, is identical with our 385 keV + 387 keV γ-rays. Considering the fact that the strongly converted 222 keV transition, which is no doubt the cascade initiator, should not be easily seen in a scintillation spectrometer, the results of Henrikson *et al.* are in good agreement with our findings.

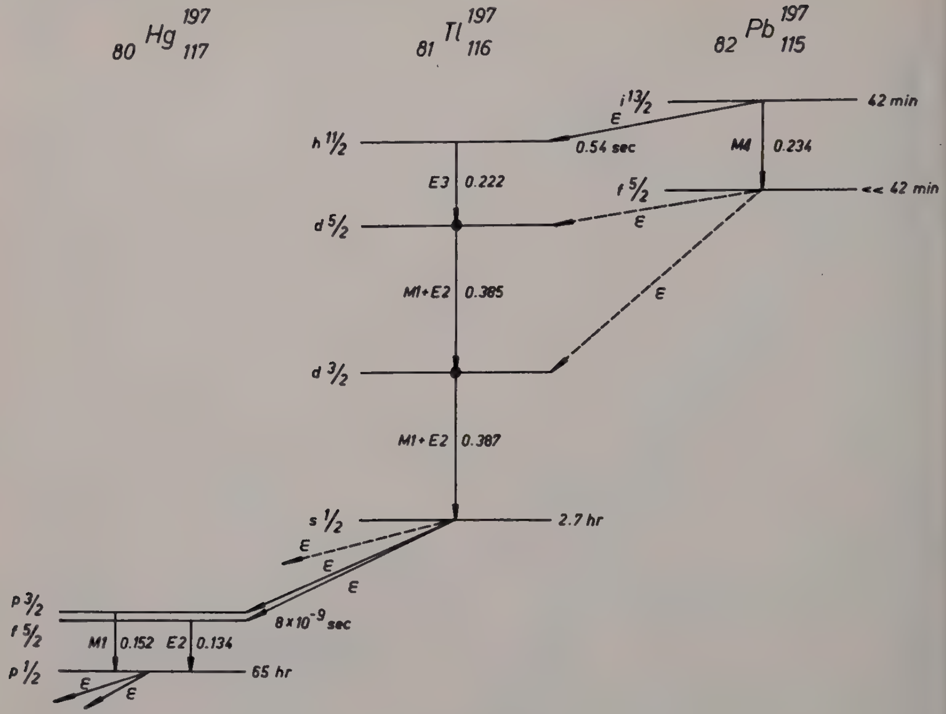

Fig. 8. Proposed decay scheme of Pb^{197} and Tl^{197}.

Previous to our investigation the 134 keV γ-ray in the decay of Tl^{197} was known from the decay of Hg^{197m} [26]. This may be considered as a further confirmation of our mass assignment. It seems reasonable to assume that the 134 keV $E2$ and the 152 keV $M1$ transitions both go to the $p_{1/2}$ ground state from $f_{5/2}$ and $p_{3/2}$ states, respectively, in analogy with the 158 keV and 208 keV transitions in Hg^{199} [5]. In the absence of coincidence measurements the position of other γ-rays in the decay scheme (Fig. 8) is uncertain.

In our preliminary report [7] some inaccurately measured ≈ 3 hr γ-rays (269, 583, 588 and 637 keV) were tentatively assigned to Tl^{197}. Knight and Baker [8] suggest that two of these transitions (583 or 588 keV and 637 keV) are identical with the 586 keV and 635 keV γ-rays observed in their study and interpreted as probably belonging to an E.C. branch from Tl^{198m}. In view of the fact that the "very strong" 261 keV isomeric transition did not show up at all in our spectra in spite of the branching ratio E.C./I.T. $\approx$ 1–2 given by Knight and Baker, their interpretation seems somewhat doubtful. The low intensities of the electron lines concerned and the similar decay rates of Tl^{197} and Tl^{196} have so far precluded the clearing up of this point.

3.5. *A* = *196*

With type A but not with type B samples conversion lines of 167 keV[1] and 253 keV γ-rays were found, having about 40 min half-life. Their assignment to Pb^{197m},

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[1] This is identical with the 169 keV transition tentatively assigned to Pb^{197} in our preliminary report [7].

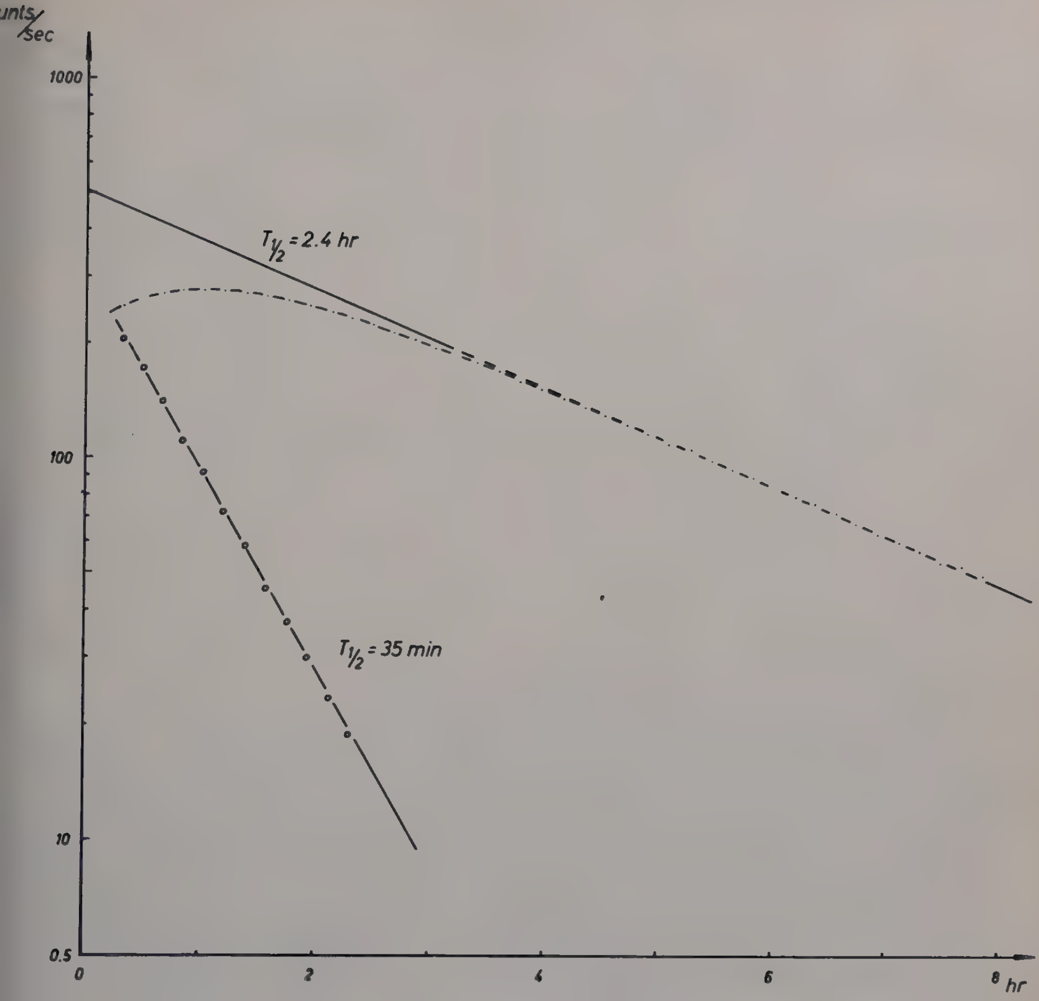

Fig. 9. Growth and decay of the K line of the 425 keV transition in Tl^{196}.

however, was not consistent with excitation relations. Furthermore, accurate half-life measurements on the K-lines gave definitely lower values than 42 min (37 ± 3 min).

Decay curves of mass 196 samples showed a 40 min component, but this was not considered conclusive because contamination from mass 197 could not be entirely excluded. The assignment of a 37 min activity to Pb^{196} is, however, supported by its genetic relationship to Tl^{196} as described below.

A 425 keV γ-ray, belonging to the Tl fraction, was assigned to Tl^{196} for the following reasons. Excitation relations indicated $A < 198$. The conversion lines were not seen in the β-spectrum of $A = 197$ in spite of their strong intensities in type B spectra. Finally, a 426 keV γ-ray following the β-decay of Au^{196} has been reported [27].

The growth and decay of the 425 keV K-line was followed in the β-spectrometer.

Table 4. Transitions in A = 196.

Nuclide	E_γ keV	E_{e^-} keV	Conversion		I_{e^-}	$K/\Sigma L$	L_{I+II}/L_{III}	Multipole order	I_{tot}	Remarks
			Shell	Element						
Pb^{196}	166.77	81.25	K	Tl	19	≈ 1				L-line badly superimp
37 ± 3 min	166.83	154.18	L_{III}							(cf. the text).
	or									
	169.20	81.25	K	Pb						
	169.38	154.18	L_{II}							
	252.9	167.4	K	Tl	100	4.7		$M1\,(+E2)$		$M1$ calc.: $K/\Sigma L = 6.$
		237.5	L_I							
Tl^{196}	424.6	341.5	K	Hg		4.4		$M1 + E2$		$E2$ calc.: $K/L = 3.3$;
2.4 ± 0.1 hr		409.8	L_I							$M1$ calc.: $K/L = 6.5$.
		420.5	M_I							*Note.* Staehelin [27] f
		423.3	N							$E2$ most probable
										the 426 ± 2 keV tra
										tion in $Au^{196} \rightarrow Hg^{196}$

2.4 hr Tl^{196} was found to grow from a 35 min parent (Fig. 9). We conclude that this is identical with the above-mentioned 37 min activity.

There is, however, still some confusion as to the origin of the two γ-transitions (167 keV and 253 keV). They have been shown to follow in cascade by $e^- - e^-$ coincidence measurements. (It may be mentioned that no coincidences were found with any of the 42 min lines assigned to Pb^{197m}.) The 253 keV γ-ray is clearly converted in Tl, but the other one is doubtful in this respect. The fact that its L-lines are masked by several other lines of different half-lives, makes the measurements unreliable. If the two electron lines found are interpreted as K and L_{III}, the sum energies agree very well with conversion in Tl (Table 4). This interpretation seems compatible only with an $M4$ transition, which should then be analogous to the isomeric transition in Tl^{198m} [6]. On this assumption, however, it would be difficult to explain why the 37 min lines were not seen with a type B sample. On the other hand, energies and intensities of the two electron lines are also consistent with an $E2$ transition in Pb ($E_\gamma = 169$ keV), in which case the lines should be K and L_{II}. This does not agree with the conversion in Tl of the 253 keV transition and the cascade relation established by coincidence measurements.

The conversion electron data are collected in Table 4.

3.6. *A = 195*

The decay curve of a mass 195 sample could be decomposed into three components: 11.4 hr (probably identical with 9.5 hr Hg^{195}), 1.2 hr and < 30 min. The 1.2 hr activity turned out to have a 37 keV γ-ray that is undoubtly identical with a transition earlier found in the decay of Hg^{195m} [28] and is thus assigned to Tl^{195}. Knight

Table 5. Transitions in A = 195.

clide	E_γ keV	E_{e^-} keV	Conversion		I_{e^-}	$K/\Sigma L$	$L_{\mathrm{I}\div\mathrm{II}}/L_{\mathrm{III}}$	Multi-pole order	I_{tot}	Remarks
			Shell	Ele-ment						
5m	99.12	84.42	L_{II}	Tl	100		1.8	*E*3 ?		*E*3 calc.: $L_{\mathrm{I+II}}/L_{\mathrm{III}} = 2.7$; *E*2 calc.: $L_{\mathrm{I+II}}/L_{\mathrm{III}} = 1.2$. Note that also the 221.9 keV γ-ray following $\mathrm{Pb}^{197\mathrm{m}}$, whose K/L ratio fits *E*3 extremely well, has $L_{\mathrm{I+II}}/L_{\mathrm{III}}$ lower than the calculated value.
1 min	99.17	86.52	L_{III}		57					
	98.91	95.73	$M_{\mathrm{II+III}}$		36					
	99.06	98.22	N		13					
	or									
	99.62	84.42	L_{II}	Pb						
	99.55	86.52	L_{III}							
	99.05	95.73	$M_{\mathrm{II+III}}$							
	99.11	98.22	N							
	393.1	307.6	K	Tl	(23)	≈ 3		*E*2 ?		
		≈378	L		(7)					
	447.5	362.0	K	Tl	(11)					
0.1 hr	37.0	22.2	L_{I}	Hg				(*M*1)		Assignment *M*1 according to Gillon *et al.* [28].
		33.6	M_{I}							
		36.4	N							

and Baker [8] report exactly the same half-life for this isotope, which they obtained by deuteron bombardment of Hg, enriched in mass 196.

It was natural to expect the short-lived component to be associated with Pb^{195}. With a type E sample, (L_{I}), L_{II}, L_{III}, M and N lines of a 17 min γ-ray ($E_\gamma = 99$ keV) were indeed seen. Energy measurements could not decide whether the conversion takes place in Pb or in Tl, though the latter seems somewhat favoured (Table 5). The L-line intensities, however, definitely exclude the multipole assignment $M4$, but are consistent with an $E3$ or $E2$ transition (Fig. 10).

By following the decay of the L_{II} line, $T_{1/2} = 17 \pm 1$ min was found (Fig. 11). Two other K-lines of the same half-life were observed.

Assuming that the 17 min activity belongs to A = 195 we suggest the following explanation of the experimental findings.

It will be recalled that no E.C. decay could be proved from $\mathrm{Pb}^{199\mathrm{m}}$, while in $\mathrm{Pb}^{197\mathrm{m}}$ a branching ratio E.C./I.T. = 4.2 was obtained. Thus it would not be surprising if $\mathrm{Pb}^{195\mathrm{m}}$ decays predominantly by electron capture, which could explain why the isomeric transition was not detected. In analogy with $\mathrm{Pb}^{197\mathrm{m}}$ the three γ-rays found should then be associated with the level sequence $h_{11/2}$, $d_{5/2}$, $d_{3/2}$ and $s_{1/2}$ in Tl^{195}. This is shown in section 4 to be in accordance with level systematics.

The above discussion leads to the proposed decay scheme of Fig. 12.

3.7. *Unassigned lines*

In Table 6 electron lines of uncertain origin have been grouped according to approximate half-life. Possible activities are indicated in the half-life column. The

Table 6. Unassigned lines.

Half-life	E_{e^-} keV	Possible assignment	Remarks
2–3 hr (2.4 hr Pb^{198} 2.7 hr Tl^{197} 2.4 hr Tl^{196})	60.0	K 146 conv. Tl	
	130.0	L 146 conv. Tl	
	185.9	K 269 conv. Hg	$K/L \approx 2$
	253.6	L 269 conv. Hg	Probably Tl^{197}
	190.3	K 276 conv. Tl	$K/L \approx 2$
	260.1	L 276 conv. Tl	
	334.5	K 420 conv. Tl	$K/L \approx 2.5$
	406.0	L 420 conv. Tl	
	351.5		Probably Tl
	392.5		Probably Pb
	490.5	K 576 conv. Tl	$K/L \approx 2.5$
	562.2	L 576 conv. Tl	
	500.0	K 583 conv. Hg	$K/L = 3.2$
	565.0	L 583 conv. Hg	
	505.0		Probably Tl
	520.3	K 606 conv. Tl	$K/L \approx 2$
	590.0	L 606 conv. Tl	
	528	K 611 conv. Hg	$K/L \approx 1$
	596	L 611 conv. Hg	
	554		Probably Tl
	605.1		Probably Pb
	657.0		Probably Pb
1–2 hr (1.5 hr Pb^{199} 1.2 hr Tl^{195})	27.4	L_{I} 42 conv. Hg	Probably Tl^{195}
	29.7	L_{II} 42 conv. Hg	
	38.7	M_{I} 42 conv. Hg	
	28.7	L_{III} 41 conv. Hg	Probably Tl^{195}
	37.2	M_{I} 41 conv. Hg	
	43.1		Probably Tl
	49.5	L 64 conv. Hg	Probably Tl^{195}
	60.3	M 64 conv. Hg	
	90.2		Probably Pb
	105.4		Probably Pb
	154		Low mass number
	181.2	K 267 conv. Tl	$K \gtrsim L$
	252.0	L 267 conv. Tl	Probably Pb^{199}
	676		Probably Pb
	682		Probably Pb
	753		Probably Pb
	852		Probably Pb
	916		Probably Pb
	1011		Probably Pb
	1027		Probably Pb
	1032		Probably Pb
	1046.0	K 1132 conv. Tl	$K/L \approx 6$ (Ml)
	1116.7	L 1132 conv. Tl	Probably Pb^{199}
	1151		Probably Pb
	1293		Probably Pb
1 hr (42 min Pb^{197m} 37 min Pb^{196})	≈ 41	L_{I}	
	≈ 42	L_{II}	
	107		
	176.5	L_{I}	
	179.2	L_{III}	

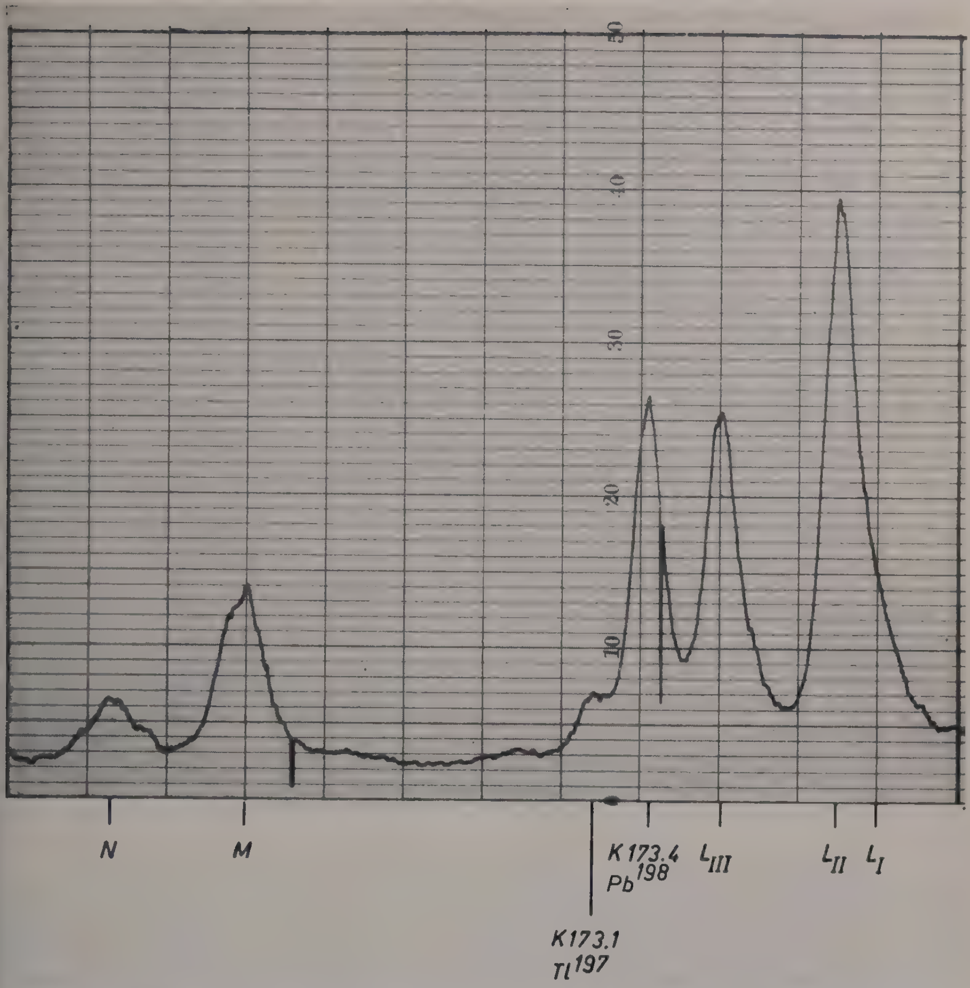

Fig. 10. Automatically recorded conversion lines of the 99 keV transition following the electron capture of Pb^{195m}. Scanning time: 6 min. Sensitivity: full scale deflection = 500 counts/sec.

energy determinations are of varying accuracy, being in many cases of the order of 0.5 %. As the lines were found in different records, no intensity comparison has been possible. Most of them are, however, weak at all bombarding energies used.

3.8. *Positron Spectrum*

As the Pb and Tl isotopes concerned are not members of any known α-decay chains, a study of possibly occurring positron spectra is the best way of establishing energy relations between isobars.

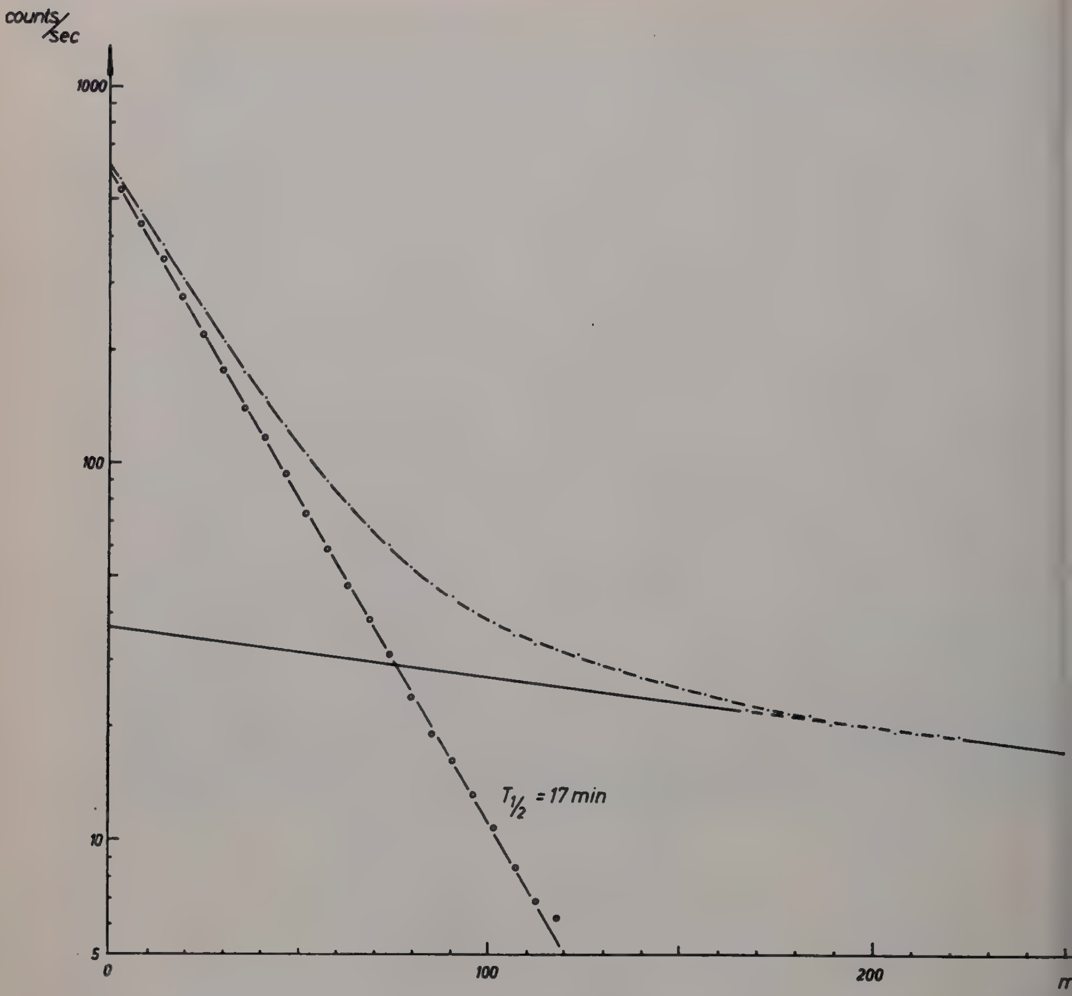

Fig. 11. Decay of the L_{II} line of the 99 keV transition following the electron capture of Pb^{195m}.

A preliminary run, using a type A sample from a 65 MeV bombardment, revealed the presence of a complicated positron spectrum. The decay of the spectrum was followed for several days and some information about the components was obtained.

After two days an apparently pure 26 hr Tl^{200} spectrum of end-point energy about 1.5 MeV remained. The intensity compared with that of the K-line of the strong 368 keV γ-ray [29] gives $K368/\beta^+ \approx 8$. These findings are in fair agreement with recent results of C.-J. Herrlander [30]: $E_{max} = 1.44$ MeV (the most energetic of three components) and $K368/\beta^+ = 10.8$.

When the earlier spectra were corrected for the growth and decay of Tl^{200}, a 10 hr component with $E_{max} \approx 2.5$ MeV appeared. This is tentatively identified as 9.4 hr Pb^{201}.

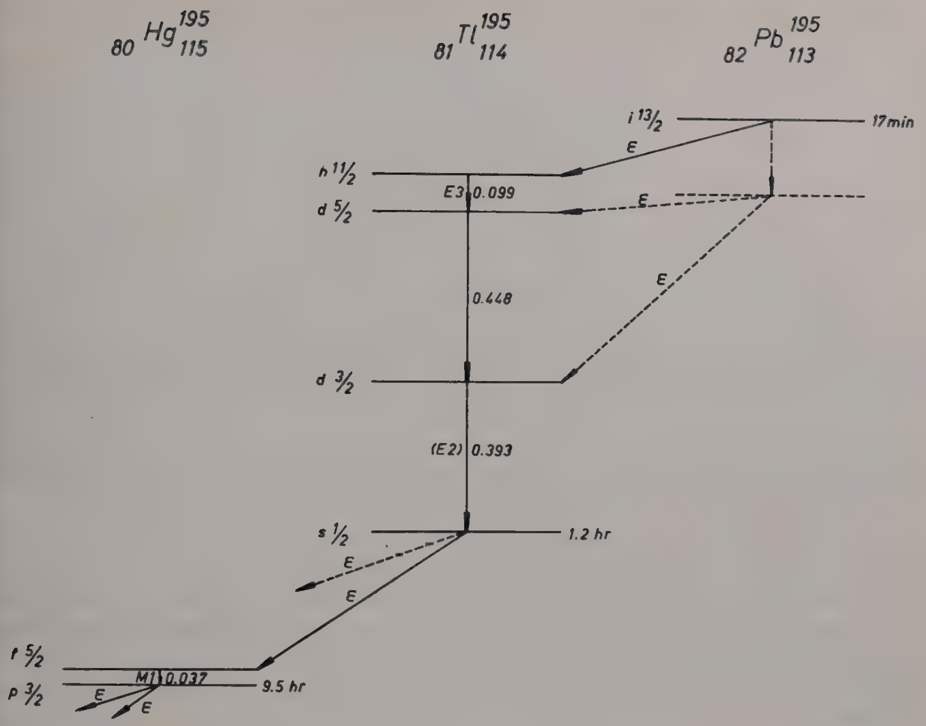

Fig. 12. Proposed decay scheme of Pb^{195} and Tl^{195}.

Finally the original spectrum, after subtraction of the long-lived components, was found to decay with a half-life of about 1.8 hr. Several activities may still have been present. From the half-life and the bombarding energy, 1.5 hr Pb^{199} and 2.3 hr Pb^{198} seem to be the most probable. An attempt at a Fermi analysis, assuming "unique" forbidden transition with $\Delta J = 2$ [31], indicates a highest end-point energy of 2.8 MeV. For intensity comparison $K353$ Pb^{199} was measured, giving $K353/\beta^+ \approx 3$.

So far the positron spectra have not been studied in more detail. This would obviously be very tedious without mass separated samples of sufficient strength, which, for the present, we are not able to prepare.

4. Energy level systematics

4.1. *Odd mass Pb isomers*

This topic was recently treated by R. Stockendal *et al.* [23], who also included our results on Pb^{199m} and Pb^{197m} in their survey. We can add only a few new facts, notably concerning E.C. branching from the high-spin isomeric state. For the sake of completeness, however, the situation will be briefly summarized.

$M4$ transitions of the well known $i_{13/2} \to f_{5/2}$ type have been proved to exist in

$$\mathrm{Pb}^{207} \text{ (0.8 sec, 1064 keV)},$$
$$\mathrm{Pb}^{203} \text{ (6.5 sec, 825 keV)},$$
$$\mathrm{Pb}^{201} \text{ (61 sec, 629 keV)},$$
$$\mathrm{Pb}^{199} \text{ (12.2 min, 424 keV)},$$

and

$$\mathrm{Pb}^{197} \text{ (42 min, 234 keV)}.$$

The transition energy decreases with decreasing neutron number along a very smooth curve. Furthermore, if the probability of radiative transition divided by A^2 is plotted as a function of transition energy in a log-log diagram, the points relating to the first four isomers fall exactly on a straight line, while Pb^{197m} shows an appreciable deviation. This was assumed to be due to the presence of an E.C. branch from the isomeric level [23].

As described in section 3.4, this branching has now been established, and the ratio

$$\text{E.C./I.T.} = 4.2 \pm 0.3$$

obtained from the intensities of the 222 keV $E3$ transition following the electron capture decay and the 234 keV isomeric transition. This is in good agreement with the value E.C./I.T. = 4.1 calculated by Stockendal *et al.* [23] from the deviation of the Pb^{197m} point from the straight line, when no correction for electron capture had been made.

It is illustrating also to calculate the radial matrix elements $\mathcal{M}$ for the $M4$ transitions. Following the treatment given by Mayer and Jensen [32] and using the nuclear radius constant $r_0 = 1.20 \times 10^{-13}$ cm, we find for

$$\mathrm{Pb}^{197m}: |\mathcal{M}|^2 = 3.8 \pm 0.5$$

and for

$$\mathrm{Pb}^{199m}: |\mathcal{M}|^2 = 3.8 \pm 0.2.$$

These values are to be compared with those obtained by Stockendal *et al.* [23].

$$\mathrm{Pb}^{201m}: |\mathcal{M}|^2 = 3.5 \pm 0.2,$$
$$\mathrm{Pb}^{203m}: |\mathcal{M}|^2 = 4.0 \pm 0.4,$$

and

$$\mathrm{Pb}^{207m}: |\mathcal{M}|^2 = 3.7 \pm 0.1.$$

From the transition energy versus neutron number curve [23] Pb^{195m} might be expected to have an isomeric transition of energy between 100 and 200 keV. No such transition could be observed, however, probably due to an intense E.C. branch from the $i_{13/2}$ state. Three γ-rays ascribable to this branch were found, settling the half-life of Pb^{195m} as 17 min (section 3.6). If a definite energy, say 150 keV, is assumed for the unobserved $M4$ transition, the ratio E.C./I.T., necessary to bring the matrix element in accord with those of Pb^{197m} and Pb^{199m}, can be calculated. We find E.C./I.T. ≈ 170, which would wholly explain why the isomeric transition was not seen in our experiments.

4.2. *Levels in odd mass Tl isotopes*

To a large extent the decay schemes presented in chapter 3 are based on analogies with nuclides of higher mass number. Especially in the odd mass Tl isotopes the regular behaviour of energy levels is very striking.

In the stable nuclei Tl^{205} and Tl^{203} the ground state assignment $s_{1/2}$ has been verified by direct measurement of spin and magnetic moment [33].

The first excited state of Tl^{203}, which decays to the ground state by a mixed $M1$ and $E2$ γ-transition [17, 34, 35, 36, 37, 38], is then certainly a $d_{3/2}$ state as predicted by the nuclear shell model. Also the prediction $d_{5/2}$ for the second excited state is in agreement with experimental findings [17, 34, 36], though a $3/2^+$ assignment cannot be excluded [20].

Equivalent conditions were found in Tl^{205} by R. Barloutaud *et al.* [38], who studied Coulomb excitation of natural Tl. Pairs of strong transitions, fitting nicely into the picture, also occur in the decays of Pb^{201} [29], Pb^{199}, Pb^{197} and Pb^{195} (this work).

On the neutron-rich side, levels in Tl^{207} are populated by the α-decay of Bi^{211} (AcC). Only one γ-ray has been found with certainty [39, 40], whose energy (353 keV) is consistent also with α-energy differences [41, 42]. K/L and α_K clearly indicate mixed $M1$ and $E2$ radiation and the transition is interpreted as $d_{3/2} \rightarrow s_{1/2}$ [40]. The energy of the second excited state in Tl^{207} is unknown. There is some evidence for a weak 85 keV γ-ray in the decay of Bi^{211} [43, 39], but no conclusions can be drawn as to its position in the decay scheme.

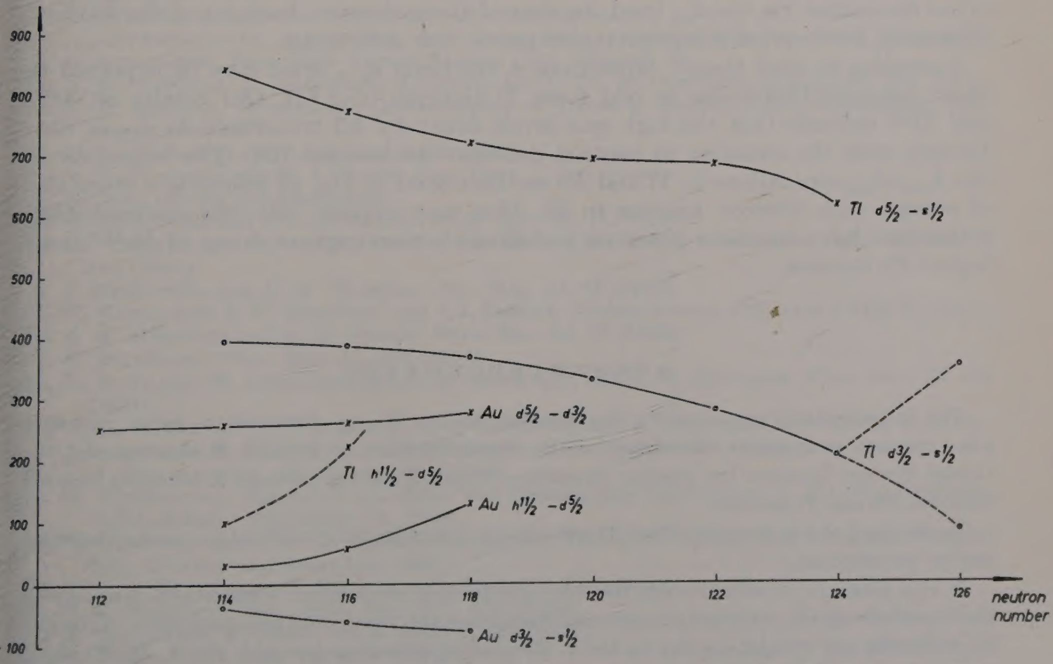

Fig. 13. Level separations in odd mass Tl and Au isotopes as a function of neutron number.

Table 7. Excited states in odd mass Tl isotopes.

Nucleus	Energy (keV) above ground state		Reference
	1st exc. state	2nd exc. state	
Tl^{207}	353	—	[42]
Tl^{205}	205	615	[38]
Tl^{203}	279	679	[17]
Tl^{201}	330	692	[29]
Tl^{199}	367	720	This work
Tl^{197}	387	772	This work
Tl^{195}	393	841	This work

In Table 7 available information regarding the first two excited states in odd mass Tl isotopes has been summarized.

Fig. 13 shows the level separations as a function of neutron number. Corresponding curves for Au [44] have been included for comparison. In these nuclei the ground state is $d_{3/2}$, and the $s_{1/2}$ and $d_{5/2}$ levels belong to different γ-ray branches [28].

The deviation of the 353 keV Tl^{207} point from the smooth $d_{3/2}$–$s_{1/2}$ curve can possibly be explained as an effect of the neutron shell closure ($N = 126$). On the other hand the uncertain 85 keV transition fits the $d_{3/2}$–$s_{1/2}$ curve extremely well, as shown in the figure. This would imply that the $d_{3/2}$ level is populated only by a very weak α-branch from Bi^{211} and that the strong 353 keV transition originates in a level that is not de-excited via the $d_{3/2}$ level. In view of the multipole character of the 353 keV transition, however, this interpretation meets with difficulties.

According to shell theory predictions a low-lying $h_{11/2}$ level may be expected to cause isomeric transitions in odd mass Tl isotopes ($Z = 81$). Our results on Tl^{197} and Tl^{195} indicate that the high spin levels decay by $E3$ transitions to $d_{5/2}$ in conformity with the situation in neutron deficient Au isotopes [28]. The behaviour of the $h_{11/2}$–$d_{5/2}$ separations in Tl and Au as illustrated in Fig. 13 points to a steep rise of energy with neutron number in Tl. This may explain why the corresponding transitions have not been observed to follow electron capture decay of Pb^{199m} and higher Pb isomers.

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REFERENCES

1. H. M. Neumann and I. Perlman, Phys. Rev. *78*, 191 (1950).
2. D. G. Karraker and D. H. Templeton, Phys. Rev. *81*, 510 (1951).
3. J. M. Hollander, I. Perlman, and G. T. Seaborg, Revs. Modern Phys. *25*, 469 (1953).
4. M. C. Michel and D. H. Templeton, Phys. Rev. *93*, 1422 (1954).
5. I. Bergström, R. D. Hill, and G. de Pasquali, Phys. Rev. *92*, 918 (1953).
6. T. O. Passell, M. C. Michel, and I. Bergström, Phys. Rev. *95*, 999 (1954).
7. G. Andersson, E. Arbman, I. Bergström, and A. H. Wapstra, Phil. Mag. *46*, 70 (1955).
8. J. D. Knight and E. W. Baker, Phys. Rev. *100*, 1334 (1955).
9. E. Arbman and N. Svartholm, Arkiv Fysik *10*, 1 (1956).
10. I. Bergström *et al.*, private communication.
11. T. R. Gerholm, Rev. Sci. Instr. *26*, 1069 (1955); Arkiv Fysik *11*, 55 (1956).
12. R. E. Bell, Bull. Am. Phys. Soc. *29*:4, 63 (1954), and private communication.
13. J. D. Jackson, Bull. Am. Phys. Soc. *29*:4, 63 (1954), and private communication (forthcoming publication in Can. J. Phys.).
14. G. Rudstam and Å. Svanheden, private communication.
15. G. Andersson *et al.*, unpublished; cf. J. Koch, Proc. 1955 Harwell Isotope Conf., Chapter 25.
16. G. Andersson, Proc. 1955 Harwell Isotope Conf., Chapter 29.
17. A. H. Wapstra, D. Maeder, G. J. Nijgh, and L. Th. M. Ornstein, Physica *20*, 169 (1954).
18. E. B. Sandell, Colorimetric Determination of Traces of Metals, p. 391. Interscience Publishers, Inc., 1950.
19. M. E. Rose *et al.*, privately circulated tables.
20. A. H. Wapstra and G. J. Nijgh, Nuc. Phys. *1*, 245 (1956).
21. L. Sliv, private communication.
22. E. L. Church and J. E. Monahan, Phys. Rev. *98*, 718 (1955).
23. R. Stockendal, J. A. McDonell, M. Schmorak, and I. Bergström, Arkiv Fysik, *11*, 165 (1956).
24. I. Bergström and A. H. Wapstra, Phil. Mag. *46*, 61 (1955).
25. A. Henrikson, S. W. Breckon, and J. S. Foster, Nuclear Science Abstracts *8*:24B, 76 (1954).
26. J. W. Mihelich and A. de-Shalit, Phys. Rev. *91*, 78 (1953).
27. P. Staehelin, Phys. Rev. *87*, 374 (1952).
28. L. P. Gillon, K. Gopalakrishnan, A. de-Shalit, and J. W. Mihelich, Phys. Rev. *93*, 124 (1954).
29. K.-E. Bergkvist, I. Bergström, C.-J. Herrlander, S. Hultberg, H. Slätis, E. Sokolowski, A. H. Wapstra, and T. Wiedling, Phil. Mag. *46*, 65 (1955).
30. C.-J. Herrlander, private communication.
31. E. Konopinski, Chapter X of "Beta- and Gamma-Ray Spectroscopy". Ed. Kai Siegbahn. North-Holland Publishing Co., 1955.
32. M. G. Mayer and J. H. D. Jensen, Elementary Theory of Nuclear Shell Structure, Chapter XII. J. Wiley and Sons, Inc., 1955.
33. P. F. A. Klinkenberg, Revs. Modern Phys. *24*, 63 (1952).
34. J. R. Prescott, Proc. Phys. Soc. *A 67*, 254 (1954).
35. S. Thulin and K. Nybö, Arkiv Fysik *7*, 289 (1954).
36. J. Varma, Phys. Rev. *94*, 1688 (1954).
37. N. Marty, Compt. rend. *240*, 291 (1955).

38. R. BARLOUTAUD, T. GRJEBINE, and M. RIOU, Compt. rend. *240*, 1207 (1955).
39. S. P. CHOONG and J. SURUGUE, J. phys. radium *9*, 437 (1938).
40. P. FALK-VAIRANT, J. TEILLAC, and C. VICTOR, J. phys. radium *13*, 313 (1952).
41. M. G. HOLLOWAY and M. S. LIVINGSTON, Phys. Rev. *54*, 18 (1938).
42. G. VIEIRA and L. SALGUEIRO, Compt. rend. *234*, 1765 (1952).
43. M. CURIE and S. ROSENBLUM, Compt. rend. *194*, 1232 (1932).
44. J. W. MIHELICH and A. DE-SHALIT, Phys. Rev. *93*, 135 (1954).

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